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CROP PRODUCTION

Sunlight transmitted by colored shade nets on photosynthesis and yield of cucumber

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ABSTRACT: *Black shading nets are widely used in the protected cultivation of vegetables as a technique for controlling light and temperature, while the colored shading nets, with special optical properties to improve the use of solar radiation, appeared recently in the agricultural plastics market. Light quality transmitted by gray, aluminized, pearl, blue, red and black (control) nets with 30% shade was evaluated, as well as its effects on photosynthetic properties and fruits production of cucumber plants. Treatments (shade nets) were established under a randomized complete block design with four repetitions. The red net transmitted 23.7 and 40.3% more photosynthetic photon flux density (400 to 700nm) and red light (600 to 700nm) and the blue net transmitted 36% more blue light (400 to 500nm) in comparison with the respective transmissions of black net. All nets increased the photosynthetic responses: transpiration, stomatal conductance and CO_2 assimilation, observed in plants grown under black net. Leaf greenness (41.6 SPAD units) and foliar area (90dm^2) increased 22.8 and 38.9% with the red net, while the dry weight of leaf (52.5g) increased 21.9% with pearl net. Pearl, red, aluminized and blue nets showed to be viable alternatives because the production of fruit increased in 71, 48, 46 and 46%, respectively, in comparison with the conventional black net (52t ha^{-1}).*
Key words: *Cucumis sativus L., light transmission, photosynthetic responses, leaf growth, fruit production.*

Luz solar transmitida por malhas coloridas sobre fotossíntese e rendimento de pepino

RESUMO: *As malhas de sombreamento preto são amplamente utilizadas no cultivo protegido de hortaliças como uma técnica para controlar a luz e a temperatura; enquanto as malhas de sombreamento coloridas, com propriedades ópticas especiais para melhorar o uso da radiação solar, apareceram recentemente no mercado de plásticos agrícolas. A qualidade de luz transmitida por malhas cinza, aluminizada, pérola, azul, vermelha e preta (controle) com 30% de sombreamento foi avaliada, assim como seus efeitos nas propriedades fotossintéticas e na produção de frutos de plantas de pepino. Os tratamentos (malhas de sombreamento) foram estabelecidos sob o desenho de blocos completos casualizados, com quatro repetições. A malha vermelha transmitiu 23,7 e 40,3% mais densidade de fluxo de fótons fotossintéticos (400 a 700nm) e luz vermelha (600 a 700nm) e a malha azul transmitiu 36% mais luz azul (400 a 500nm) em comparação com as respectivas transmissões de malha preta. Todas as malhas aumentaram as respostas fotossintéticas: transpiração, condutância estomática e assimilação de CO_2, observadas em plantas cultivadas sob malha preta. O verde da folha (41,6 unidades SPAD) e a área foliar (90dm^2) aumentaram 22,8 e 38,9% com a malha vermelha, enquanto o peso seco da folha (52,5g) aumentou 21,9% com a malha pérola. As malhas pérola, vermelha, aluminizada e azul mostraram-se como alternativas viáveis, pois a produção de frutos aumentou em 71, 48, 46 e 46%, respectivamente, em comparação à malha convencional preta (52t ha^{-1}).*
Palavras-chave: *Cucumis sativus L., transmissão de luz, respostas fotosintéticas, crescimento foliar, produção de frutos.*

INTRODUCTION

Cucumber (*Cucumis sativus* L.) is cultivated worldwide for several purposes: fresh consumption, pickle and cosmetics industries, mainly. In 2014 were harvested 2.18 million hectares and 74.98 million tons of fruit produced (FAO, 2017).

Greenhouse represents an option to increase cucumber production, by promoting an environment that improves the growth and development of plants (ORTIZ et al., 2009; YANG et al., 2012). However, building a greenhouse means a large investment that needs to be carefully considered. For this reason, it should be structural designs that adapt to the different needs of each crop and available resources. An economical alternative is the net house or shade net, which protects horticultural plants (leaf and fruit) from strong direct sun radiation, obtaining more vigorous plants, with higher yields and fruits of better quality than in the open field (GRUDA, 2005; AYALA-TAFOYA et al., 2011).

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Shading nets made of different materials, such as polyethylene, polypropylene and polyester or acrylic derivatives, have different rates of transmission, absorption and reflection of light and air porosity (TEITEL, 2007; AL-HELAL & ABDEL-GHANY, 2010). Most agricultural nets used for these purpose are black and little or nothing photoselective, that is, reduce both the transmission of photosynthetically active radiation (PAR) such as near infrared (AYALA-TAFOYA et al., 2011). Horticulturists to reduce solar radiation and temperature ordinarily use such nets (LEGARREA et al., 2010; MILLER et al., 2015). Moderate shading (30-50%) protect fruits from sunburns, reduce water use and resulted in high yields of good quality; however, more intensive shading reduce leaf photosynthesis and adversely affect productivity (SHAHAK et al., 2008; ZHU et al., 2012; DÍAZ-PÉREZ, 2013).

Plastic nets with special optical properties recently developed represent a new approach to improve the use of solar radiation in agricultural crops (GANELEVIN, 2008). Are colored shade nets, each of which specifically modifies the transmitted light spectrum in the ultraviolet, visible and far red regions, enriching the relative content of scattered light and affects its thermal components (infrared region), in function of the chromatic additives of plastic, scattering elements and weaving design (SHAHAK et al., 2004). Thus, black, grey and white nets have effect of reduction of light quantity (neutral shade), while red, blue, yellow and pearl nets have effect of changes in red and blue light composition (photo-selective shade) (COSTA et al., 2010; AYALA-TAFOYA et al., 2011; LOBOS et al., 2012; OLIVEIRA et al., 2016). In addition, pearl, white, red, blue and yellow nets increase scattered light ratio at luminous environment of cultivated plants (OREN-SHAMIR et al., 2001; SHAHAK et al., 2004, 2008; ILIĆ & FALLIK, 2017).

The application of photo-selective netting technology is gaining popularity around the world, especially in Mediterranean countries (BASILE et al., 2008; FALLIK et al., 2009; GOREN et al., 2011; BASTÍAS et al., 2012; KONG et al., 2013; KITTA et al., 2014), but also in other countries such as Serbia (MILENKOVIĆ et al., 2012; ILIĆ et al., 2015), Hungary (OMBÓDI et al., 2015), South Africa (SELAHLE et al., 2014; MASHABELA et al., 2015), Brazil (SANTANA et al., 2012; OLIVEIRA et al., 2016), and Mexico (AYALA-TAFOYA et al., 2011; MARTÍNEZ-GUTIÉRREZ et al., 2016).

Light transmission through these cover materials promotes the differential stimulation of some physiological responses regulated by light, such as photosynthesis, as a function of photosynthetic photon flux density (PPFD) and leaf content of a and b chlorophylls (ILIĆ et al., 2015; MARTÍNEZ-GUTIÉRREZ et al., 2016; BUTHELEZI et al., 2016; ILIĆ & FALLIK, 2017). According to the literature, photo-selective shading nets changed plant growth and leaf anatomy (BRANT et al., 2009; BASTÍAS & CORELLI-GRAPPADELLI, 2012; OLIVEIRA et al., 2016; MARTÍNEZ-GUTIÉRREZ et al., 2016), and incremented fruits yield and quality (BASTÍAS et al., 2012; KONG et al., 2013; TINYANE et al., 2013; MASHABELA et al., 2015; ILIĆ et al., 2015, 2017) of different cultivated vegetables, but about cucumber there is not information.

Research was carried out for knowing the transmission of photosynthetic radiation of six colored shade nets, its effects on the photosynthetic properties, leaf growth of plants and fruits yield, which can lead to replacement of the black shade net and increase the competitiveness of the cucumber producer under net house conditions.

MATERIALS AND METHODS

The research was carry out during the autumn-winter horticultural stage of Sinaloa, Mexico, in a net house (Casa sombra, ACEA, Mexico) located at coordinates 24° 48' 30" N and 107° 24' 30" W, and 38.5m of altitude. Structural characteristics of the net house are; metallic structure of 4.55m height, gable roof, oriented north to south, with 80m long and 40m wide for a total area of 3200m^2. The roofing is a high-density polyethylene (HDPE) woven monofilament net with 16x10 crystalline threads per cm^2 (Anti-aphid net, Fibras Plasticas, Mexico) of 25% shade, and HDPE woven monofilament net with 20 crystalline threads x 10 black threads per cm^2 (Anti-thrips bicolor net, Fibras Plasticas, Mexico) with 50% shade in walls.

After tilling the soil, culture beds were formed distanced 1.8 m and mulched with coextruded plastic white/black of 25μm of thickness. Meanwhile, cucumber seeds (Modan F1, Rijk Zwaan, Mexico), parthenocarpic slicer type, were sown in 200-well polystyrene trays filled with a mixture of peat (Brown 025W, Kekkila, Finland) and perlite (Multiperl® horticulture, Mexico) in a ratio of 75:25 (v/v). Seedlings were grown in a greenhouse (Baticenital, ACEA, Mexico), as conventionally do it horticulturalists of the region, and were transplanted to the net house when seedlings had two true leaves, with a density of 2.2 plants/m^2. During 125-day culture cycle were applied

225, 75, 296, 178 and 22kg of nitrogen, phosphorus, potassium, calcium and magnesium per hectare, respectively, by fertigation. The cultivation cycle was concluded when the plants reached the height of the horizontal tutors of the net house (3.5m), and then apical shoot of plants were eliminated.

Treatments were six plastic nets: gray, pearl, blue, and red (ChromatiNet®), an aluminized net (Aluminet 'O'), and a black net as a control (Polysack Industries, Israel). All nets of raschel type, manufactured with mono-directional HDPE strips, stabilizers against ultraviolet radiation, and hole size 6x8mm for 30% shade. Treatments (nets) were established under a randomized complete block design, with four replicates, using as experimental plot, four culture beds of 10m long (72m^2), and as useful plot the two central beds, leaving one culture bed (1.8m) on each side and a band of equal length at each end to avoid the edge effect. In addition, each plot was separated from the others by 7.5m of area without shade net, to avoid the influence of scattered light within adjacent color nets. The shade nets were placed before transplant, 0.5m above the horizontal tutors of the net house.

Spectral photon flux measurements, in the range from 350 to 1050nm at 1nm intervals were carried out by means of a portable spectro radiometer (Field SpecPro®VNIR, ASD, USA) which was equipped with a remote cosine receptor (2π steradian field of view) located at 50cm above the ground. Spectral data were expressed as solar photon flux distribution (SPFD) in quantum unit (μmol m^{-2} s^{-1} nm^{-1}). All measurements were made under clear sky conditions between 11:00 to 13:00h (local time) during months of the experimental period (Oct-Feb), at an interval of 3min, alternately in the open air, inside of shade house and in the middle of each colored shade net. From the SPFD measured in the open air and inside the net house, integrals of solar photon flux (μmol m^{-2} s^{-1}) in the PAR wave band from 400 to 700nm (PPFD), the blue waveband from 400 to 500nm (blue light) and the red waveband from 600 to 700nm (red light) were calculated.

Outside net house and in the middle of each colored shade net was installed a thermo-hygrometer/data logger (DT171, CEM, Colombia) programmed to record temperature and relative humidity of the air every 30 minutes.

For the measurements corresponding to gas exchange: transpiration rate (E, mmol m^{-2} s^{-1}), stomatal conductance (gs, mmol m^{-2} s^{-1}) and photosynthetic CO_2 assimilation rate (A, μmol m^{-2} s^{-1}) a portable photosynthesis system (LCpro+, ADC BioScientific, UK) was used. Measurements were made on 16 fully expanded sheets. These variables were measured monthly (30, 60 and 90 days after transplant) under environmental conditions of clear sky, between 9:00 and 12:00h (local time), in plants located in the central area of each shade net.

Using sixteen cucumber plants per treatment leaf greenness were measured (30, 60 and 90 days after transplant) with a chlorophyll meter (SPAD-502Plus, Konica Minolta, Japan), leaf area with a portable leaf area meter (LI-3000A, LI-COR Inc., USA), and leaf dry weight using a precision scale (CP622, Sartorius, Germany) after oven drying (FE-292, Felisa, Mexico) to 70°C until constant dry weight. Fruit growth was evaluated by measuring the length and diameter of 16 fruits, every three days until its harvest. The harvest carried out three times a week, recording the number, size and weight of fruits.

The results obtained in each study variable were submitted to analysis of variance and Duncan's multiple range test ($P \leq 0.05$) for comparison of means, through STATISTICA version7 (STATSOFT, 2004).

RESULTS AND DISCUSSION

The average SPFD curves, as well as air temperature and relative humidity obtained outside and inside of the net house, and under colored shade nets, during the experimental period are shown in figure 1. Blue, red and pearl nets were those that most altered the spectrum or quality of light. Blue net transmitted more light in the blue-green region (400 to 570nm) and increased the infrared radiation flux from 730nm onwards, red net transmitted the highest photon flux from 590nm onwards; while the pearl net differed from the aluminized and gray nets increasing its transmission from 650nm. However, the nets did not affect the air temperature and the relative humidity was lower under the black net.

The greatest PPFD and red light occurred under the red net, which exceeded in 23.7 and 40.3% to the respective fluxes transmitted by the black net (Table 1). Meanwhile, the highest blue light transmission obtained with the blue net was 36% higher than that recorded with the black net. These results showed the ability of the black net to block the incident radiation and explain its wide use as shading net, while revealing the photo-selective transmission/shading of the colored nets. OREN-SHAMIR et al. (2001), SHAHAK et al. (2004) and AYALA-TAFOYA et al. (2011) also indicated similar changes in quantity and quality of light because of color and design of nets, after its evaluation in cultivation of ornamental plants (*Pittosporum variegatum*), fruits (*Vitis vinifera*,

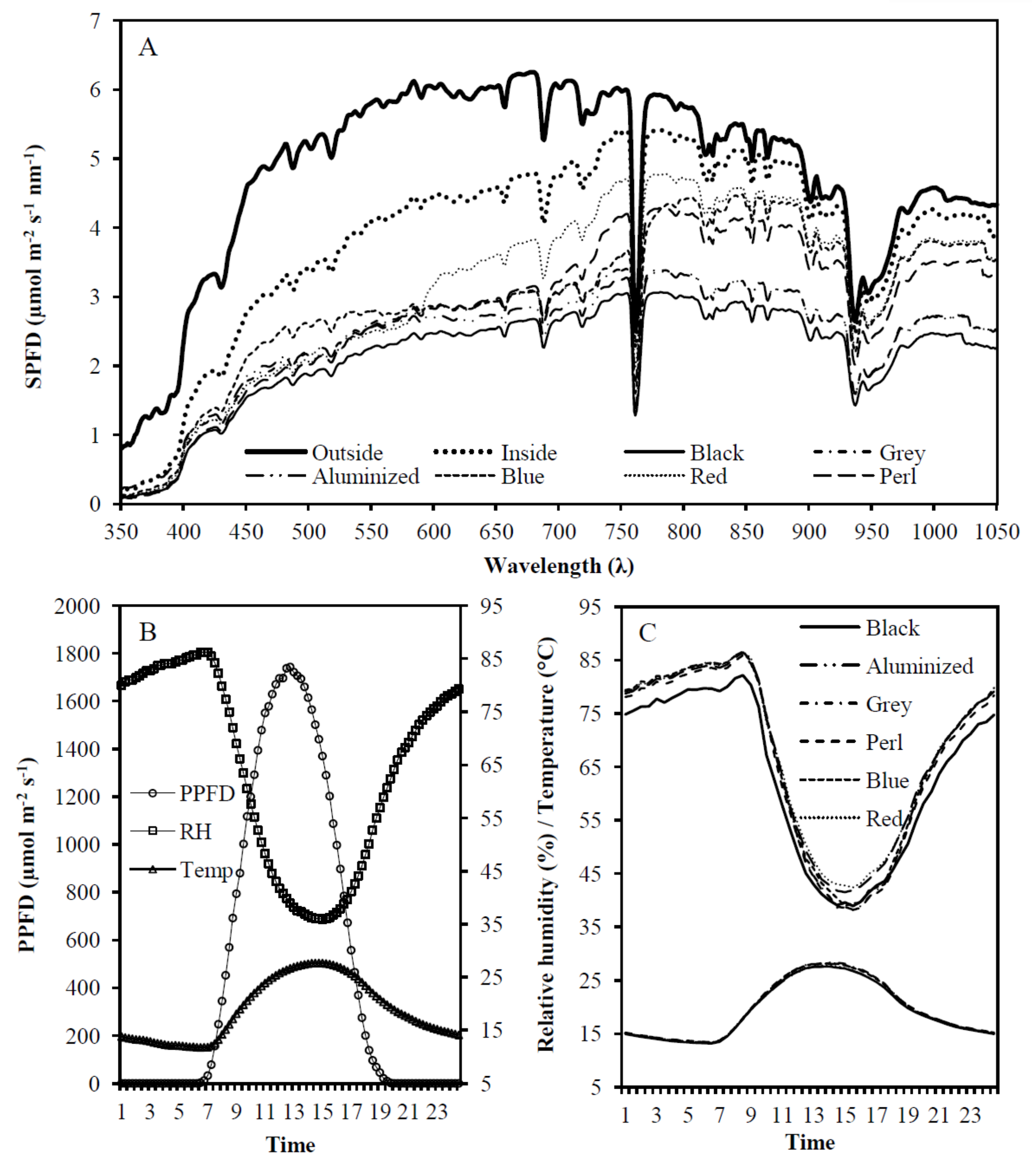

Figure 1 - Solar photon flux distribution (SPFD) outside, inside the net house, and under the influence of colored shade nets (A), measured between 11:00 and 13:00 h. Outdoor photosynthetic photon flux density (PPFD), air temperature and relative humidity (B), and air temperature and relative humidity under the influence of colored shade nets (C), for an average day of the experimental period (Oct-Feb).

Malus domestica, *Pyrus communis*, *Prunus persica*, *Diospyros kaki* and *Fragaria ananassa*) and tomato (*Solanum lycopersicum*), respectively.

In general, red, pearl, blue and aluminized nets caused the main changes in gas exchange variables in cucumber plants (Table 2). Under these

Table 1 - PPFD, blue and red light (µmol m^{-2} s^{-1}) transmitted by shade nets to the 'Modan' cucumber plants. Average for the experimental period (Oct-Feb).

	PPFD	Blue light	Red light
Shade net	(400-700nm)	(400-500nm)	(600-700nm)
Black	615.2±4.6d*	141.8±1.7f	255.4±2.0e
Aluminized	690.0±1.8c	169.2±1.3b	274.9±2.3d
Grey	707.5±5.5b	162.3±1.6c	293.7±2.1c
Perl	695.4±3.6c	150.4±1.4e	298.8±2.7b
Blue	759.7±4.2a	192.9±1.4a	295.2±2.0bc
Red	761.2±5.9a	158.8±1.6d	358.4±2.6a

PPFD = photosynthetic photon flux density. *Means ± standard error with different letters in each column are statistically different (Duncan, P≤0.05).

nets, the cucumber leaves presented transpiration rates (*E*) that surpassed from 6.9 to 44.8%, but more consistently the first three nets, to that registered under the black net. In addition to the increase of *E* according to the level of solar radiation transmitted by the nets, it also observed that *E* decreased during ontogeny of cucumber plants under all nets, which agrees with MEDRANO et al. (2005).

Additionally, with red, pearl, blue and aluminized nets, stomatal conductance (*gs*) increased from 70.8 to 125%, while CO_2 assimilation rates (*A*) also exceeded 18.4 to 37.9%, compared to the values obtained with the black net. Results obtained by JANOUDI et al. (1993) in cucumber leaves that showed maximum rates from *A* to *gs*>256mmol m^{-2} s^{-1}, while *E* continued increasing until *gs* of 380mmol m^{-2} s^{-1}, coincided with results obtained with red, pearl, blue and aluminized nets. Those responses were promoted by greater light transmissions, not only in intensity but also in quality, referred mainly to its blue light component, with great influence on stomata development (adaxial and abaxial density, polar and equatorial diameter, etc.) (MARTINS et al., 2009) and stomatal opening (HOGEWONING et al., 2010), and

Table 2 - Responses of transpiration (*E*), stomatal conductance (*gs*) and CO_2 assimilation (*A*) of 'Modan' cucumber leaves to the light transmitted by the shade nets.

Variable	Shade net	30DAT	60 DAT	90DAT
E	Black	2.6±0.5b*	2.9±0.1c	2.5±0.1c
(mmol m^{-2} s^{-1})	Aluminized	4.4±0.4a	3.1±0.1bc	2.7±0.2abc
	Grey	3.6±0.6ab	3.0±0.3bc	2.6±0.2bc
	Perl	3.7±0.2ab	3.5±0.1abc	3.5±0.3a
	Blue	4.2±0.6ab	4.2±0.4a	3.4±0.5ab
	Red	3.0±0.6ab	3.7±0.1ab	3.1±0.1abc
gs	Black	241.7±69.0b*	173.3±31.5b	230.0±9.3b
(mmol m^{-2} s^{-1})	Aluminized	526.7±76.7a	263.3±15.5a	256.7±22.6b
	Grey	343.3±83.3ab	245.6±38.6ab	221.7±14.7b
	Perl	405.0±23.3ab	325.6±8.0a	293.3±29.4ab
	Blue	540.0±108.6a	311.1±40.1a	346.7±47.9a
	Red	415.0±119.6ab	275.6±12.5a	291.7±12.5ab
A	Black	10.9±0.7b*	10.8±0.6b	10.3±0.5d
(µmolm^{-2} s^{-1})	Aluminized	13.9±0.4a	12.2±0.4ab	12.2±0.3bc
	Grey	11.6±0.5b	11.9±0.5ab	11.3±0.4cd
	Perl	14.0±0.8a	13.4±1.0a	13.8±0.4ab
	Blue	15.1±1.2a	13.0±1.2ab	14.2±1.1a
	Red	14.5±0.8a	13.3±0.6a	14.2±0.3a

DAT = days after transplant. *Means ± standard error with different letters in each column are statistically different (Duncan, P≤0.05).

red light, whose energy is more efficiently absorbed by the chlorophylls and transferred to the reaction centers, thus extending energy capture that acts effectively in the photochemical reactions (LAWSON et al., 2011). Photosynthetic responses exhibited by plants under the gray net were statistically the same as those observed in the black net (Table 2). In addition, in these two nets were presented *gs*<256mmol m^{-2} s^{-1} that apparently limited the availability of CO_2 and had repercussions on lower photosynthetic rates (JANOUDI et al., 1993; SAVVIDES et al., 2012). SHAHAK et al. (2004) observed similar responses in 'Golden Delicious' apple trees cultivated with black, gray, pearl, blue and red nets. They indicated that; although, nets reduced PAR by approximately 30%, the photosynthesis rate and the stomatal conductance of exposed leaves were higher during most of the day, compared to the measurements obtained in the control plants without net and, that the highest photosynthesis rate was obtained with the red net.

Environment created by the nets significantly influenced the growth of cucumber plants. The leaf greenness, leaf area, and leaf dry weight (Table 3), increased due to the interaction of higher PPFD and red light transmitted by the red net. Due to the effects in these variables, pearl and aluminized nets were placed second, which transmitted the second largest flows of red light and blue light, respectively. These light levels favored the photosynthesis that led to increase the biomass production, which generally implies a greater area of phloem (BARZEGARGOLCHINI et al., 2017; NAZ et al., 2018) and; consequently, a more efficient transport, and greater reserve capacity of assimilates for later use in the fruit filling (MURCIA et al., 2016). Aspects that were enhanced by enrichment of the environment with diffuse light, spectrally modified by the pearl, aluminized, red and blue nets, and photosynthetically more efficient than direct light due to its greater capacity to penetrate the vegetal canopy (OREN-SHAMIR et al., 2001; ILIĆ & FALLIK, 2017). Colored shading nets can increase light scattering by 50% or more (SHAHAK et al., 2004, 2008). Conversely, the blue net promoted high values of leaf greenness, which are usually associated with increases in PPFD and blue light transmission (COSTA et al., 2010), aspects in which it was emphasized, while plants with the lowest growth were those cultivated with black and gray nets, in each one of the variables studied.

Light environment created by plastic nets and influence of these on plant physiology affected the average fruit weight and number of fruits per plant (Table 4). With aluminized, pearl, blue and red nets, the average weight of cucumber fruits increased by between 6.9 and 8.7%, due to the positive effect on the increase of plant biomass (fruits and vegetative parts) by increasing solar radiation available and efficiency photosynthetic, promoting the increase in the growth rate of individual fruits and a shorter growth period from anthesis to harvest. This, together with an increase in the number of fruits per plant, generally results in increased production (MILENKOVIĆ et al., 2012). MARCELIS et al. (2004) reported that when the plants have a larger leaf area, there is a greater source of photo-assimilates responsible for fruit growth and/or to supply a greater number of fruits, as the percentage of abortions significantly decreased in plants.

The colored nets increased the yield of cucumber, which was significantly higher with the pearl (71%), red (48%), aluminized and blue (46%) nets, compared with the yield obtained with the black net (52t ha^{-1}), which was lower in 17% than that obtained with the gray net (Table 4); although, there were no statistical differences between them. These results agree with those observed by SHAHAK et al.

Table 3 - Influence of shade nets on growth characteristics of 'Modan' cucumber plants.

	Leaf greenness[£]	Leaf area	Leaf dry weight
Shade net	(Spad units)	(dm^2/plant)	(g/plant)
Black	41.6±1.0b[*]	90.0±3.8b	52.5±2.2b
Aluminized	47.6±1.2a	121.7±3.3a	59.3±3.0ab
Grey	44.2±1.3b	99.1±3.6b	54.8±2.7b
Perl	49.1±0.9a	116.7±6.1a	64.0±3.4a
Blue	49.7±1.5a	102.9±3.6b	53.3±2.5b
Red	51.1±1.2a	125.4±5.8a	57.5±4.0ab

[£]Average of three monthly measurements. [*]Means ± standard error with different letters in each column are statistically different (Duncan, P≤0.05).

Table 4 - Influence of shade nets on ‘Modan’ cucumber fruit production.

Shade net	Average fruit weight (g/fruit)	Number of fruits (fruits/plant)	Fruits yield (t ha^{-1})
Black	279.0±5.7b*	18.5±1.4c	51.9±4.7b
Aluminized	303.2±5.5a	25.2±0.4b	76.5±1.9a
Grey	291.8±2.6ab	20.8±1.8bc	60.7±4.8b
Perl	300.9±4.1a	30.1±2.5a	88.7±8.3a
Blue	298.9±7.2a	25.2±1.0b	76.0±3.7a
Red	298.3±2.8a	25.3±1.2b	77.1±2.2a

*Means ± standard error with different letters in each column are statistically different (Duncan, P≤0.05).

(2008) and ILIĆ et al. (2017), who used red and pearl raschel nets with 30 to 40% of shade and obtained yields of sweet pepper of 62 to 135% higher than those obtain with the black net of the same shade level. In the same way, they agree with the results achieved by AYALA-TAFOYA et al. (2011) in tomato cultivated with black, gray, aluminized, blue, red and pearl nets, each one with 50 and 30% shade, within a greenhouse. They reported that the pearl net of 30% of shade promoted the highest yields, total and with quality for export, and that with black and aluminized nets with 50% shade obtained lowest yields.

CONCLUSION

Colored nets altered the quality of the solar radiation that reached cucumber plants. Red and blue nets transmitted more PPFD, but red net transmitted more red light, and blue net transmitted more blue light; while black net transmitted the smaller flows of the three wavelength intervals.

In addition, with the colored nets also increased physiological activities related to the gas exchange: transpiration rate, stomatal conductance and photosynthetic CO_2 assimilation rate.

The cucumber yield obtained with blue, aluminized, red or pearl net increased from 46 to 71% the yield obtained with the conventional black net. Therefore, according to the results of this investigation, any of those nets that is available, but preferably the pearl, represents an option to replace the black net and increase the yield of cucumber under net house conditions.

DECLARATION OF CONFLICTING INTERESTS

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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